On the Sensitivity of Numerical Wind Field Modeling

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WindSim AS

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Content

WindSim AS

Variation in Annual Energy Production, AEP

Parameter sensitivities in the AEP calculation

Pre-processing

Processing, Simulations
- Cosine hill

Post-processing
- Ridge

Conclusion

windsim
When the terrain gets rough

WindSim AS

1993	VECTOR AS; CFD consulting
1993	Oil & Gas
1997	Wind Energy – Wind resource assessment, Norwegian Wind Atlas – Micro-siting
2003	WindSim, PC software for simulation of local wind fields
2005	VECTOR AS was divided in two companies – WindSim AS; Sale, support and development of WindSim – VECTOR AS; Consulting

WindSim office: Jarlsø, 3124 Tønsberg, Norway

AEP – lower than estimated

Wind farm owners frequently experience that the annual energy production (AEP) from their wind farms are lower than the estimated production.

This serious problem is now addressed by the wind energy sector world wide.

CFD simulations are used to get more accurate simulation results.

What are the important lessons learned, what parameters affect the quality of results?

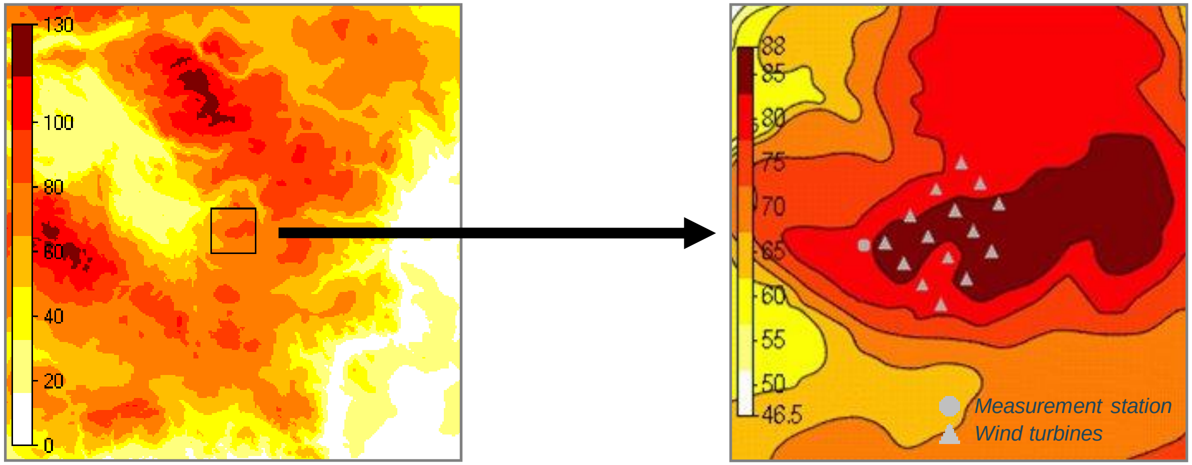
AEP variation within a wind farm

Simple terrain - Denmark

Complex terrain - Norway

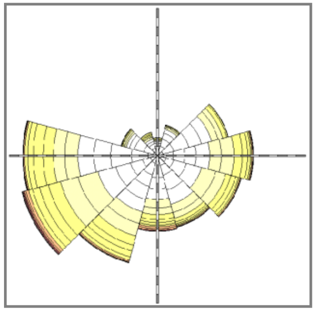
Simple terrain

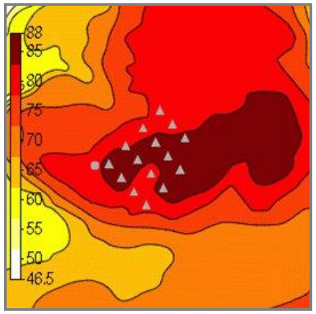
Location:	Torrild, Denmark, simple terrain
Wind farm:	15 Bonus 150 kW turbines with 30 meters hub height, height variation within the wind farm is 6 meters
Climatology:	February to October 2000, measurement height 30 meters, mean wind speed 5.6 m/s
Models:	Nesting, 20x20 km into 2x2 km with resolution 20x20 meters, number of cells is 200 000

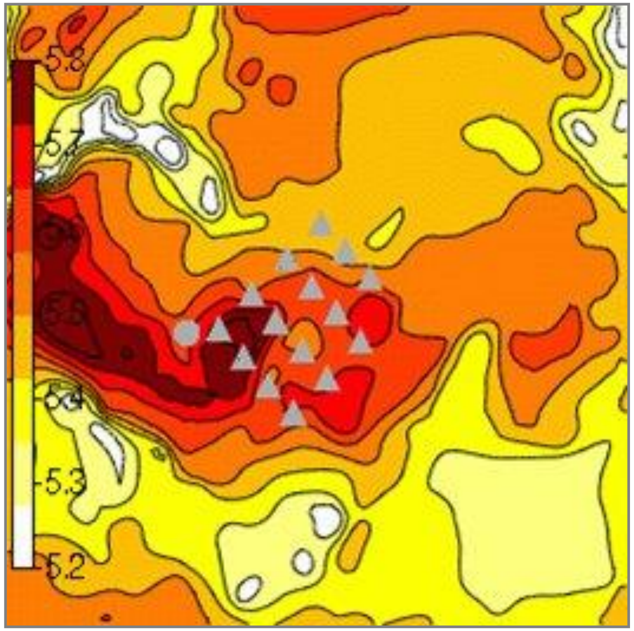


Digital terrain model with elevation in meters. Left side 20x20 km model, right side 2x2 km model with a 20x20 meters grid resolution

Simple terrain – Resources



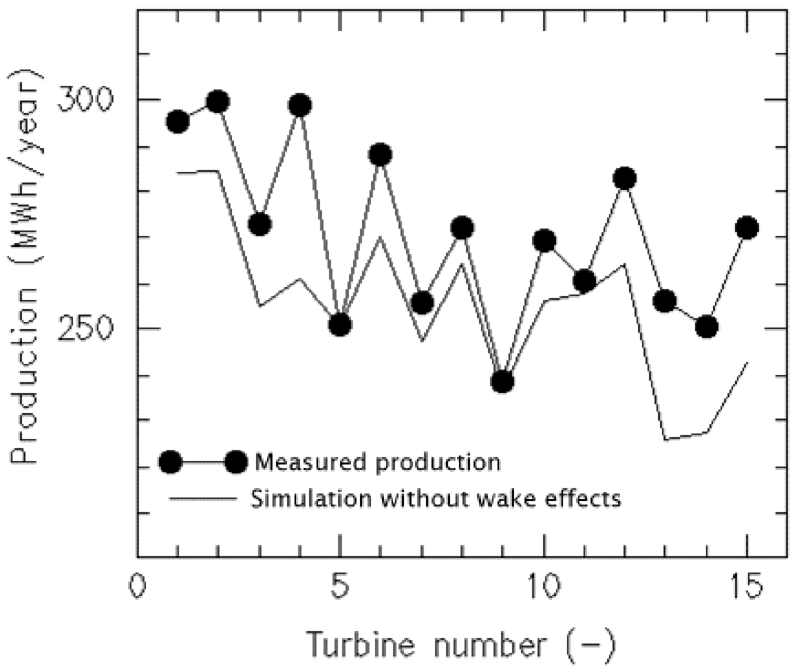




Wind resource map at 30 meters height

There is no simple coincidence between high wind speed areas and high altitude areas. Simulations shows that areas west of the wind farm display the best wind conditions. This area has terrain gradients perpendicular to the main wind directions, giving significant speed-ups.

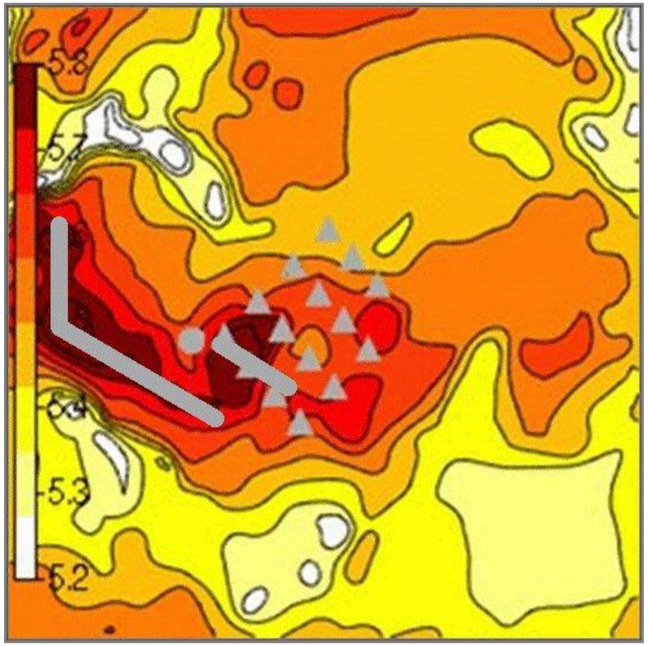
Simple terrain – AEP



The difference in energy output between the various turbines is 25%.
Wake effects is not included.

Simple terrain – Optimization

Alternative locations along the grey lines would according to simulation give a 10% increase in AEP



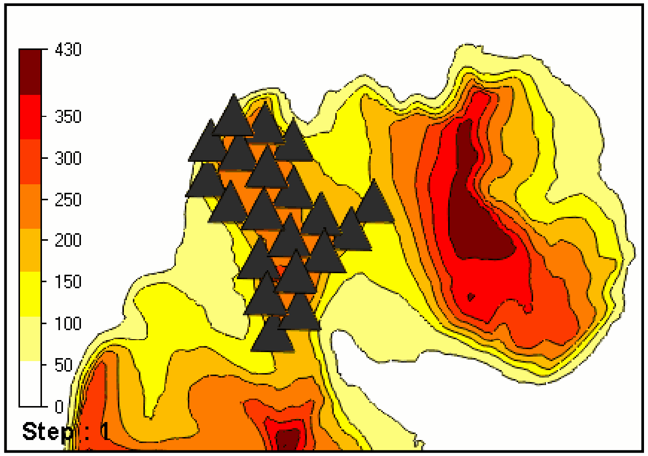
Wind resource map at 30 meters height

Paper: Gravdahl A.R., Rorgemoen S., Thogersen M., *Power prediction and siting - When the terrain gets rough*, The World Wind Energy Conference and Exhibition, Berlin, 2002.

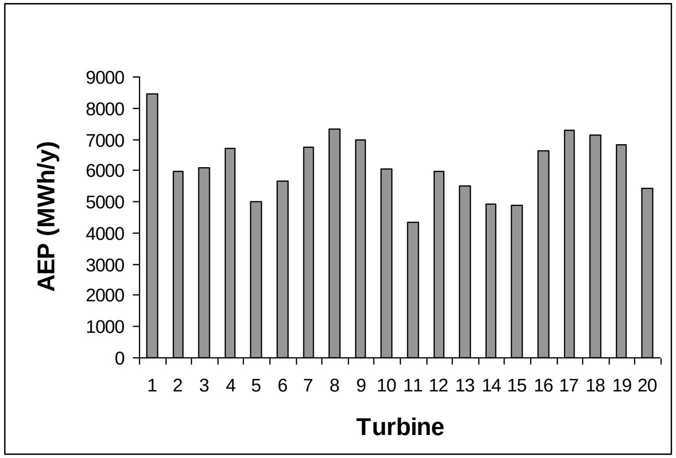
Complex terrain – AEP

Location: Norway, complex terrain

Wind farm: 2 MW turbines with 80 meters hub height, height variation within the wind farm is in the order of 100 meters.



Digital terrain model with elevation (m).



Annual energy production based on simulations, AEP (MWh/y)

The production varies between 8468 and 4356 MWh/y according to the simulations. The difference in energy output between the various turbines is in the order of 100%.

AEP variation within a wind farm

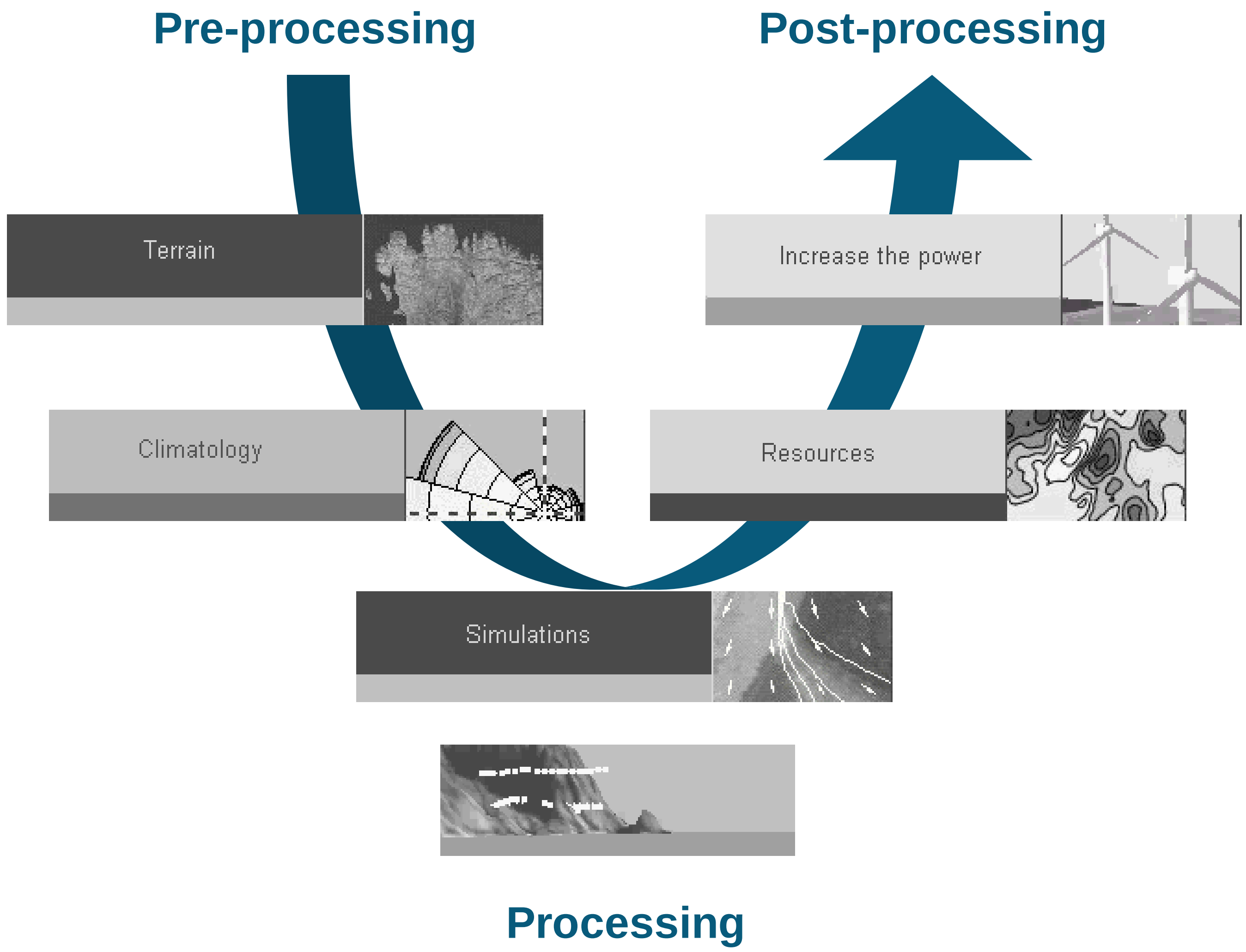
Summary:

Large variations within a wind farm in both simple and complex terrain.

Next:

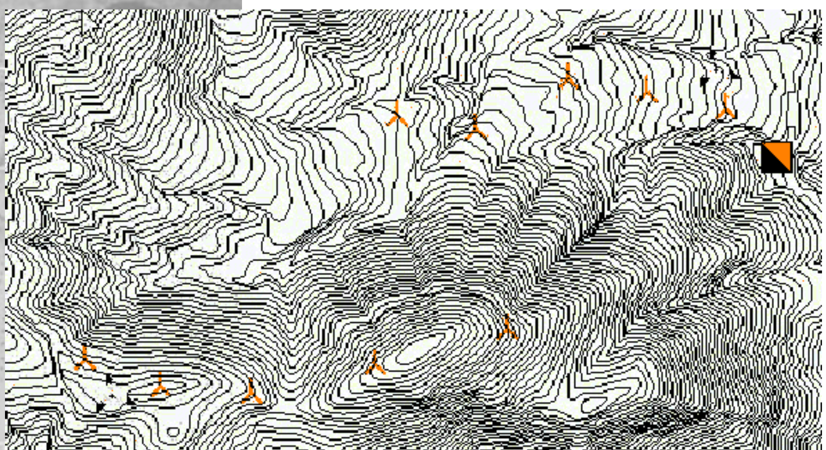
Parameter sensitivities

AEP – Estimation procedure

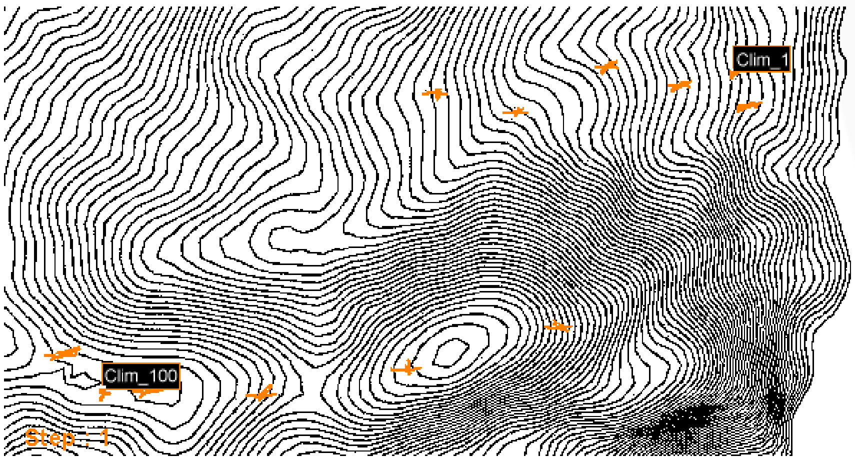


Terrain conversion

Conversion from contour lines to a regular grid will smooth the grid.



Original elevation contour lines



Elevation contour lines after conversion to a regular grid with 30x30meters resolution

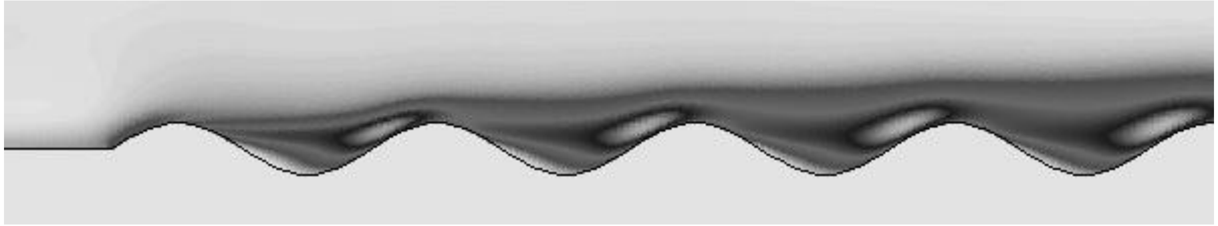
Simulation method

The method is based on the solution of the Reynolds Averaged Navier-Stokes equations, given in standard notation by:

$$\frac{\partial U_i}{\partial x_i} = 0$$

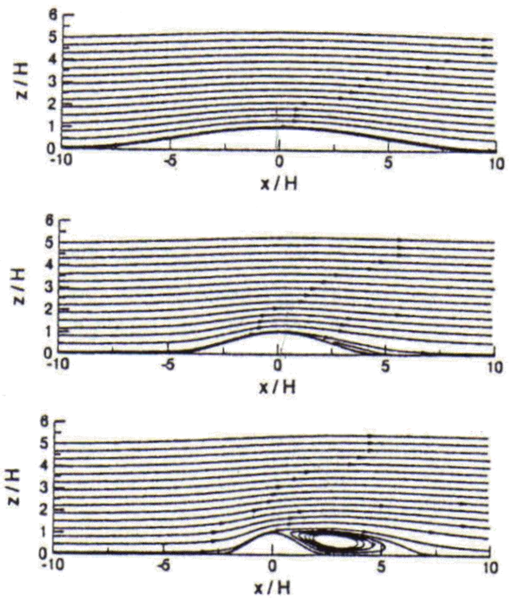
$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \overline{u_i u_j} \right) + F_i$$

Solving the non-linear transport equations for mass, momentum and optionally also the energy makes the method suitable for simulations in both complex terrain, and in situations with complex local climatology.

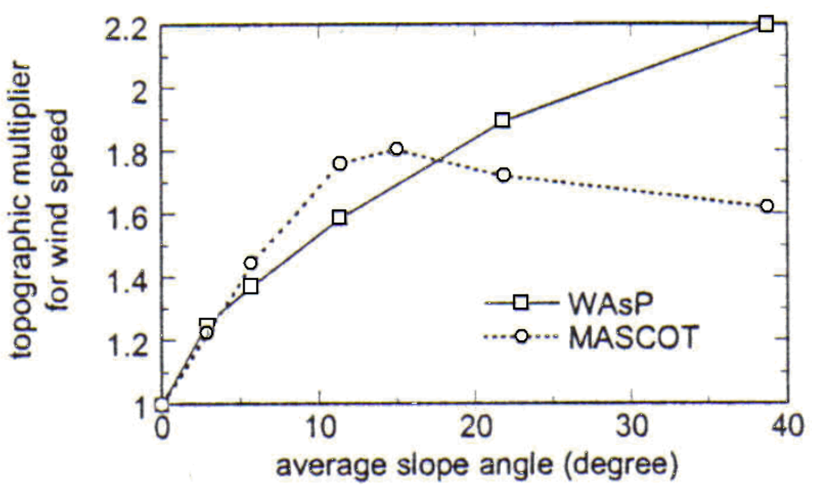


Transport of the turbulent kinetic energy in an idealized 2D sinusoidal terrain, illustrating the development of a turbulent boundary layer.

Linear versus non-linear methods



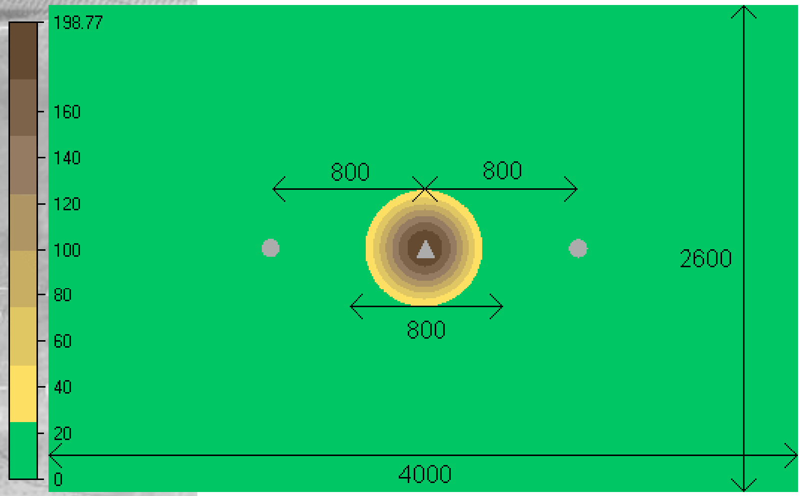
Streamlines over 2D ridge with average slope angle of 5.7, 11.3 and 21.8 degrees.

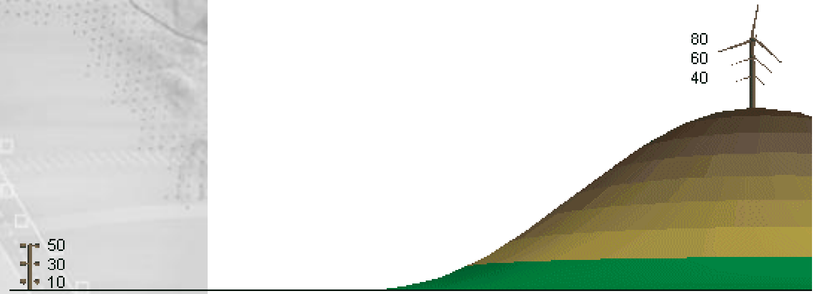


Upstream speed-up, (speed hill top)/(speed inlet)

Paper: Ishihara T., Yamaguchi A. and Fujino **Y.,** *A Nonlinear model for predictions of turbulent flow over steep terrain*, The World Wind Energy Conference and Exhibition, Berlin, 2002.

Cosine hill – terrain data





Measurement station
Wind turbines

Elevation:

$z = H \cos^2(\pi SQRT(x^2 + y^2)/2L)$ $\quad SQRT(x^2 + y^2) < L$

$z = 0$ $\quad SQRT(x^2 + y^2) \geq L$

where

H = 200 meters

L = 400 meters

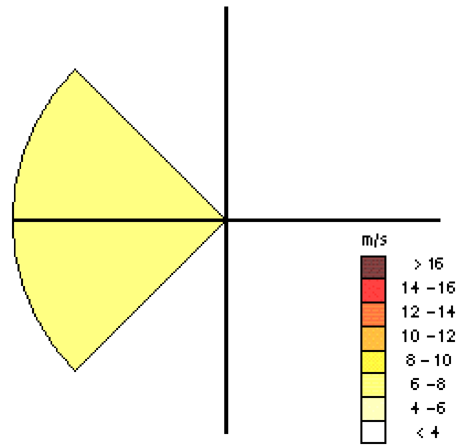
The maximum inclination angle is 40°

Roughness heights:

$z_0 = z_{land}$ $\quad SQRT(x^2 + y^2) < L$

$z_0 = z_{sea}$ $\quad SQRT(x^2 + y^2) \geq L$

Cosine hill - climatology



Sector	1	2	3	4
k	-	-	-	10.33
A	-	-	-	7.77
Frequency	0.00	0.00	0.00	1.00
Mean speed	0.00	0.00	0.00	7.50

Weibull (k,A), frequency (-) and mean wind speed (m/s) versus sector.

Cosine hill – model input

Grid:

Resolution	– Cell size in the horizontal plane
Height	– Distance from the hill top to the upper boundary
NZ	– Number of cells in the z-direction
Factor	– Distribution factor for refining the grid towards the ground

Roughness:

Z_{land}	– Roughness height for areas with elevation larger than 0
Z_{sea}	– Roughness height for areas with elevation equal to 0

Boundary conditions:

BL Height	– Boundary layer height
BL Speed	– Speed above the boundary layer
Nesting	– Initial and boundary conditions obtained by nesting

Physical models:

Transient	– Inclusion of the transient term in the transport equations
Temp.	– Inclusion of the transport equation for temperature
Turb. mod.	– Turbulence closure

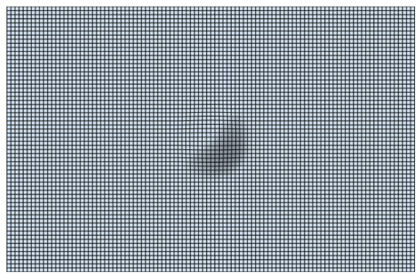
Solution procedure:

Iterations	– Number of iteration performed in the solution procedure
Solver	– Segregated versus Coupled solver

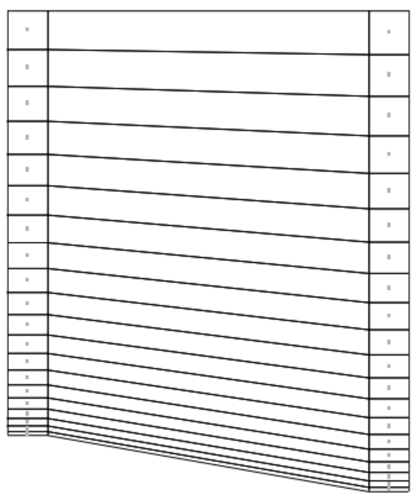
Cosine hill – reference case

Terrain	Resolution	Height	NZ	Factor	#cells	z_{land}	z_{sea}
	40x40	1500	20	0.1	139986	0.03	0.03
Wind Fields	BL Height	BL Speed	Iterations	Solver	Nesting	Turb. mod.	Temp.
	500	10.0	300	Seg.	No	k-eps	No

Reference case ID 1000



Resolution:
40x40 meters, approximately140 000 cells
.



Vertical direction:
Height 1500 meters, 20 cells, distribution factor of 0.1. Distribution of the first 5 nodes in z-direction: 6.8, 23.7 47.0, 76.8, 113.0 meters

Blocking:
Setting the height of the computational domain to 1500 meters above the highest point in the terrain, gives a blocking less than 2%.

Cosine hill – cases

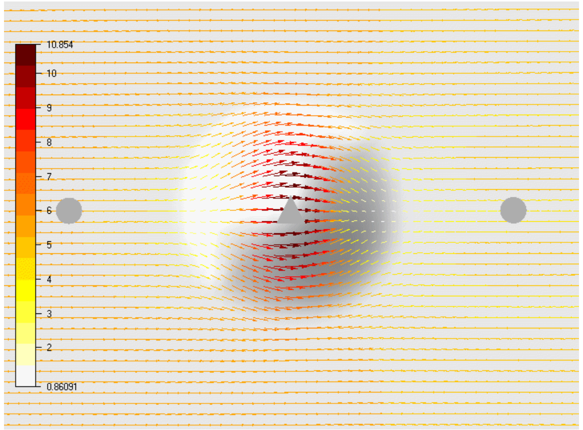
ID	1000	2000	3000	1001	1002	1100	1200
Resolution	40x40	40x40	**20x20**	40x40	40x40	40x40	40x40
Height	1500	1500	**1000**	1500	1500	1500	1500
NZ	20	20	**30**	20	20	20	**30**
Factor	0.1	0.1	0.1	0.1	0.1	0.1	**0.05**
#cells	139986	139986	**425971**	139986	139986	139986	139986
z_{land}	0.03	0.03	0.03	0.03	0.03	0.03	0.03
z_{sea}	0.03	0.03	0.03	0.03	0.03	**0.001**	0.03
BL Height	500	500	500	**250**	**1000**	500	500
BL Height	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Iterations	300	**1500**	**3000**	300	300	300	300
Solver	Seg.	Seg.	Seg.	Seg.	Seg.	Seg.	Seg.
Nesting	No	No	**Yes**	No	No	No	No
Turb. mod.	k-eps	k-eps	k-eps	k-eps	k-eps	k-eps	k-eps
Temp.	No	No	No	No	No	No	No

Cosine hill cases, changes to the reference case ID 1000 are marked with red.

Cosine hill – ID 2000

	WECS_40	WECS_60	WECS_80	AEP (Gwh/y)
Upstream_clim_10	1.98	1.93	1.91	19.16
Upstream_clim_30	1.58	1.55	1.53	15.27
Upstream_clim_50	1.45	1.42	1.40	13.04
Downstream_clim_10	2.67	2.61	2.57	18.56
Downstream_clim_30	2.14	2.09	2.07	19.66
Downstream_clim_50	2.01	1.97	1.94	19.34

Speed-up and AEP for case ID 2000

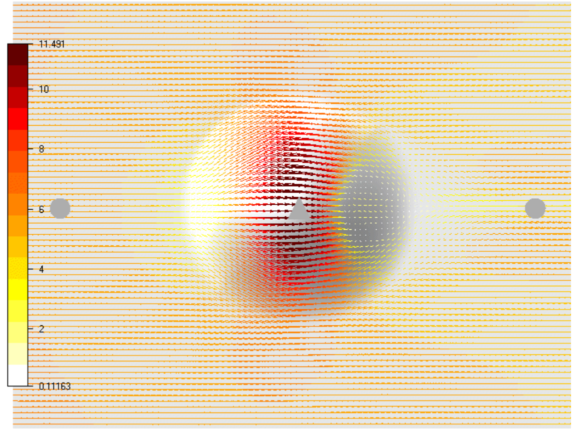


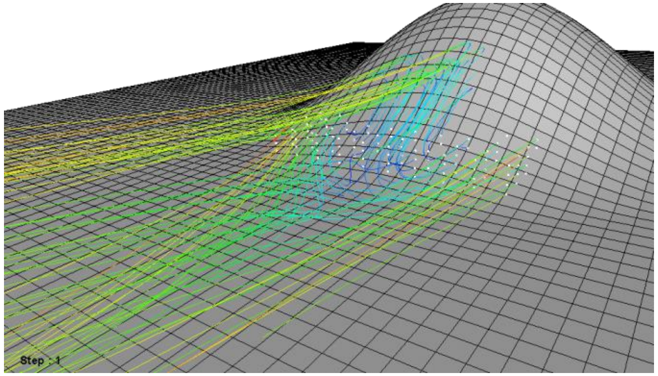
3D velocity vectors 10 meters above the ground

Cosine hill – ID 3000

	WECS_40	WECS_60	WECS_80	AEP (Gwh/y)
Upstream_clim_10	1.88	1.84	1.82	18.51
Upstream_clim_30	1.55	1.51	1.50	14.73
Upstream_clim_50	1.43	1.40	1.38	12.62
Downstream_clim_10	2.43	2.38	2.35	19.25
Downstream_clim_30	2.30	2.25	2.22	19.61
Downstream_clim_50	2.35	2.30	2.22	19.49

Speed-up and AEP for case ID 3000





3D velocity vectors 10 meters above the ground

Cosine hill

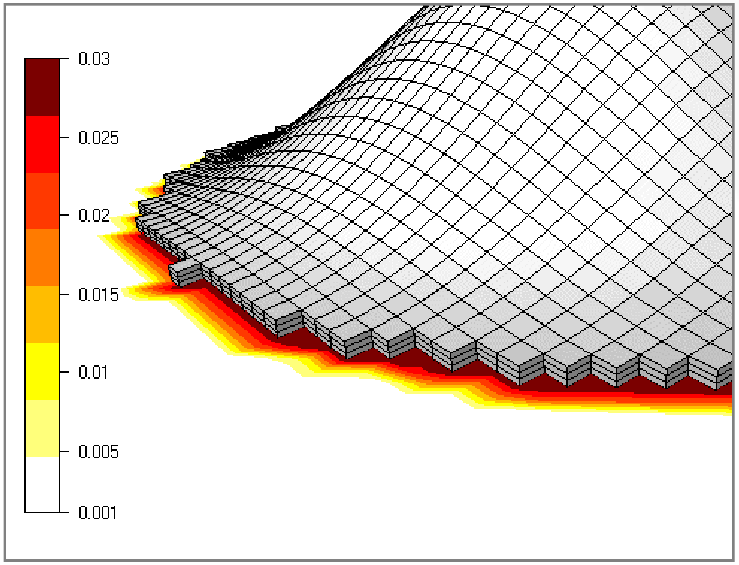
Dowmstream climatology	10	30	50	comment
AEP1000/2000 %	103.66	86.98	83.51	Increase the number of iterations

Upstream climatology	10	30	50	comment
AEP1000/2000 %	99.32	99.67	100.77	Increase the number of iterations
AEP1000/3000 %	102.81	103.33	104.12	Finer resolution - separation
AEP1000/1001 %	99.37	98.70	99.85	Reduced boundary layer height
AEP1000/1002 %	100.42	101.13	100.84	Increased boundary layer height
AEP1000/1100 %	115.33	115.74	112.02	Sea surface roughness
AEP1000/1200 %	102.64	101.13	101.94	Finer resolution vertical direction

- Slower convergence downstream
- Separation requires 20x20 meters resolution, 40° inclination
- Less sensitive to boundary profile
- Very sensitive to roughness changes
- No significant changes with a finer grid in z-direction

Cosine hill – forest

ID	No forest	Forest
Min. res.	15x15	15x15
Height	800	800
NZ	30	30
Factor	0.1	0.1
#cells	460350	460350
z_{land}	0.03	Forest
z_{sea}	0.001	0.001
BL Height	500	500
BL Height	10.0	10.0
Iterations	400	**4000**
Solver	Coupled	Seg.
Nesting	No	No
Turb. mod.	k-eps	k-eps
Temp.	No	No



Forest height (m)	#cells	Porosity	Drag coeff (C2)
10	3	0.38	0.2

Setting for two similar cases with and without a forest

Dowmstream climatology	10	30	50	comment
AEP (No forest)/(forest) %	117.24	126.09	129.44	Large sensitivities to vegetation

Differences in AEP with and without a forest

AEP parameter sensitivities - processing

Summary:

Some processing parameters display large AEP sensitivities.

Next:

The AEP procedure requires inclusion of climatology data and turbine characteristics.

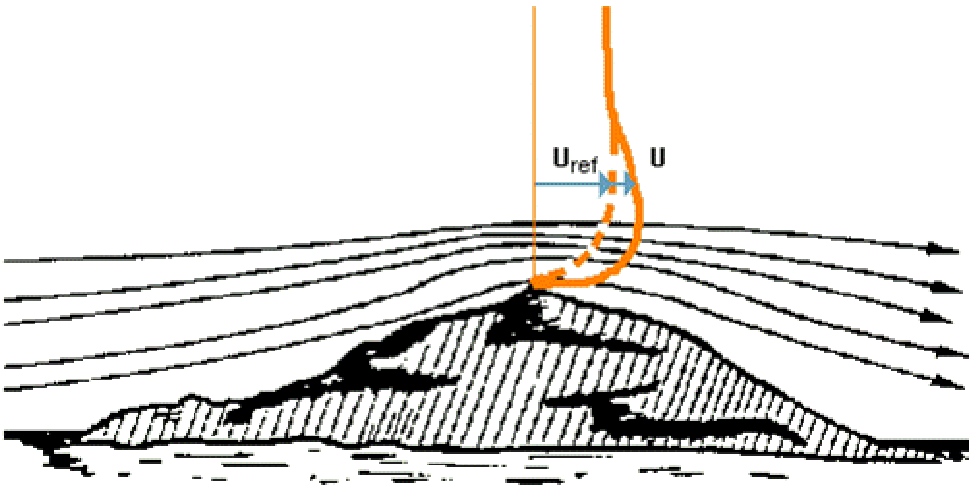
We will look at post-processing parameter sensitivities.

AEP sensitivity – Post-processing

- Climatologies represented by frequency distribution

- Power curve correction

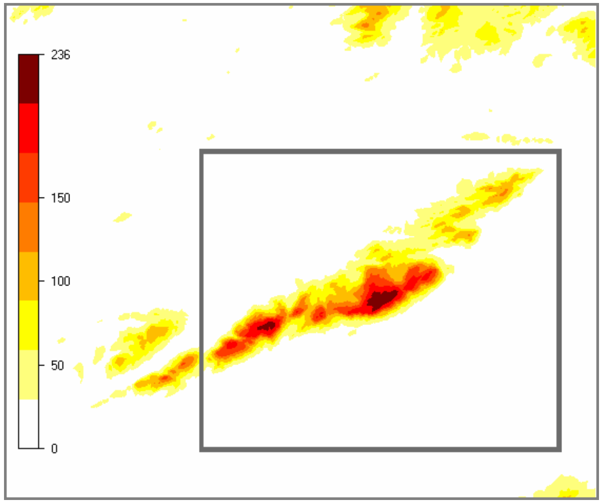
The above sensitivities are illustrated with the micro-siting at Hundhammerfjellet a typical ridge situation with negative shear profiles.



U_{ref} refers to speed over a flat area, U refers to the perturbed speed over a hill top. The speed-up is given as U/U_{ref}

Hundhammerfjellet – 2D ridge

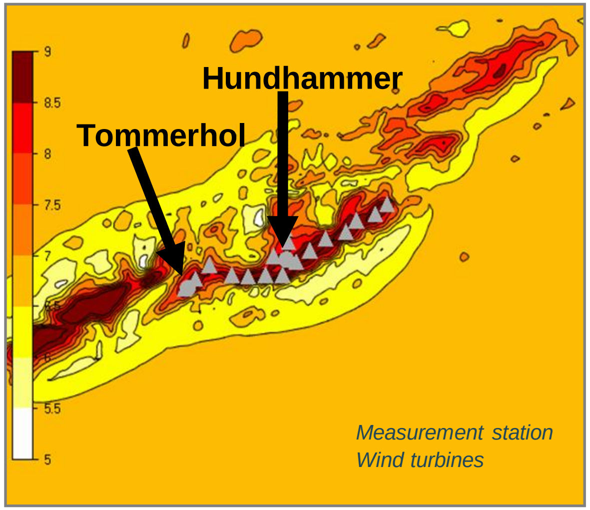
Location:	Hundhammerfjellet, Norway
Wind farm:	Under construction, 15 turbines, 3-3.5 MW ScanWind, 80 meters hub height, height variation within the wind farm is 60 meters
Climatology:	Two measurement masts, 30 and 50 meters high
Models:	Nesting, 15x15 km into 9x7,5 km with resolution 30x30 meters, number of cells is 800 000



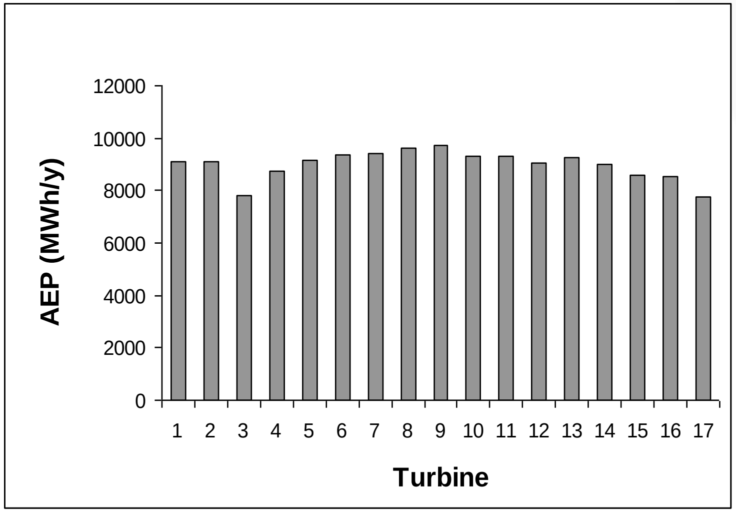
Digital terrain model with elevation. 9x7.5 km model in grey frame

Hundhammerfjellet, photomontage

Hundhammerfjellet – Resources



Wind resource map at 80 meters



AEP based on simulations (MWh/y)

The difference in energy output between the various turbines is 23%

AEP based on climatology Tommerhol is 175.0 GWh/y
AEP based on climatology Hundhammer is 179.0 GWh/y

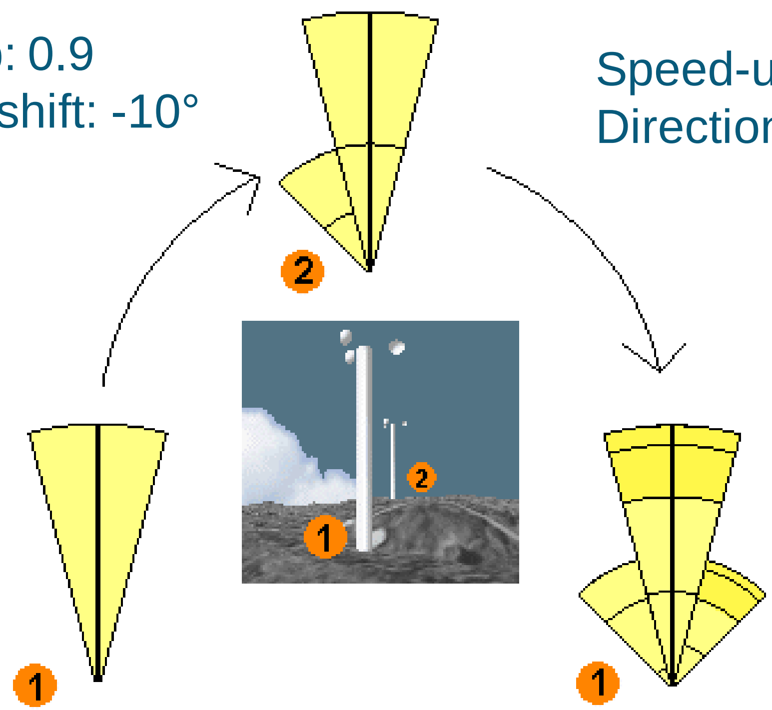
The discrepancy in estimated AEP is 2.3 %.

Climatology transfer

The discrete representation of a climatology as a frequency distribution introduces interpolation errors

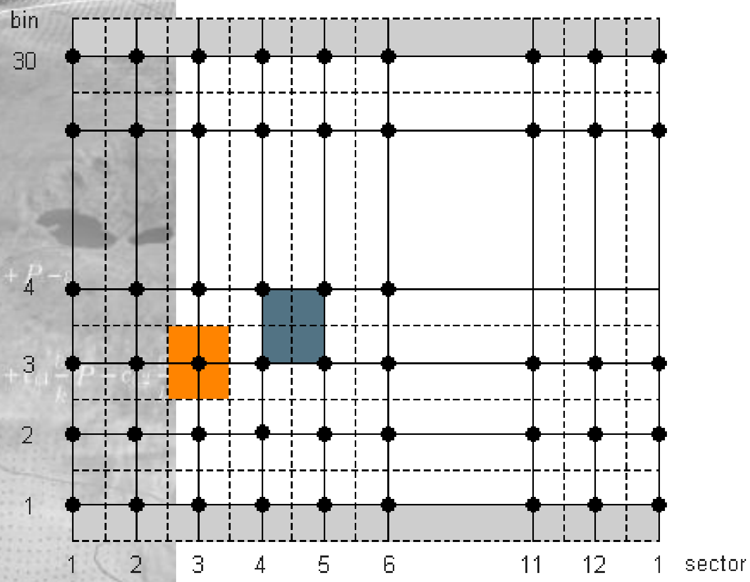
Speed-up: 0.9
Direction shift: -10°

Speed-up: 1.11
Direction shift: 10°

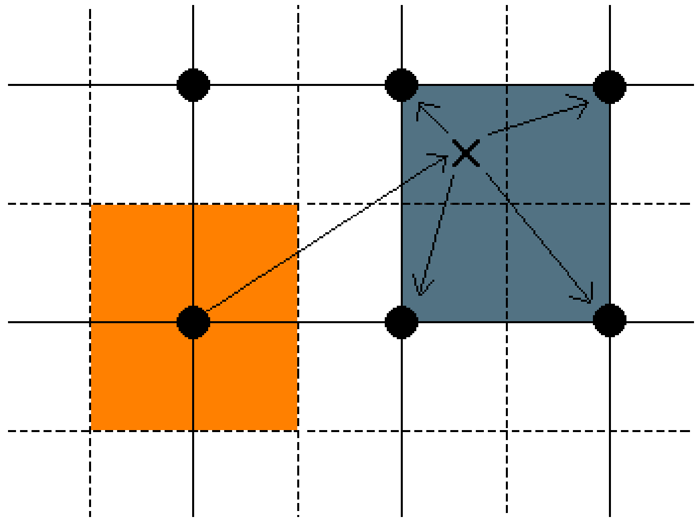


windsim
When the terrain gets rough

Re-distribution of transferred climatology



Frequency distribution

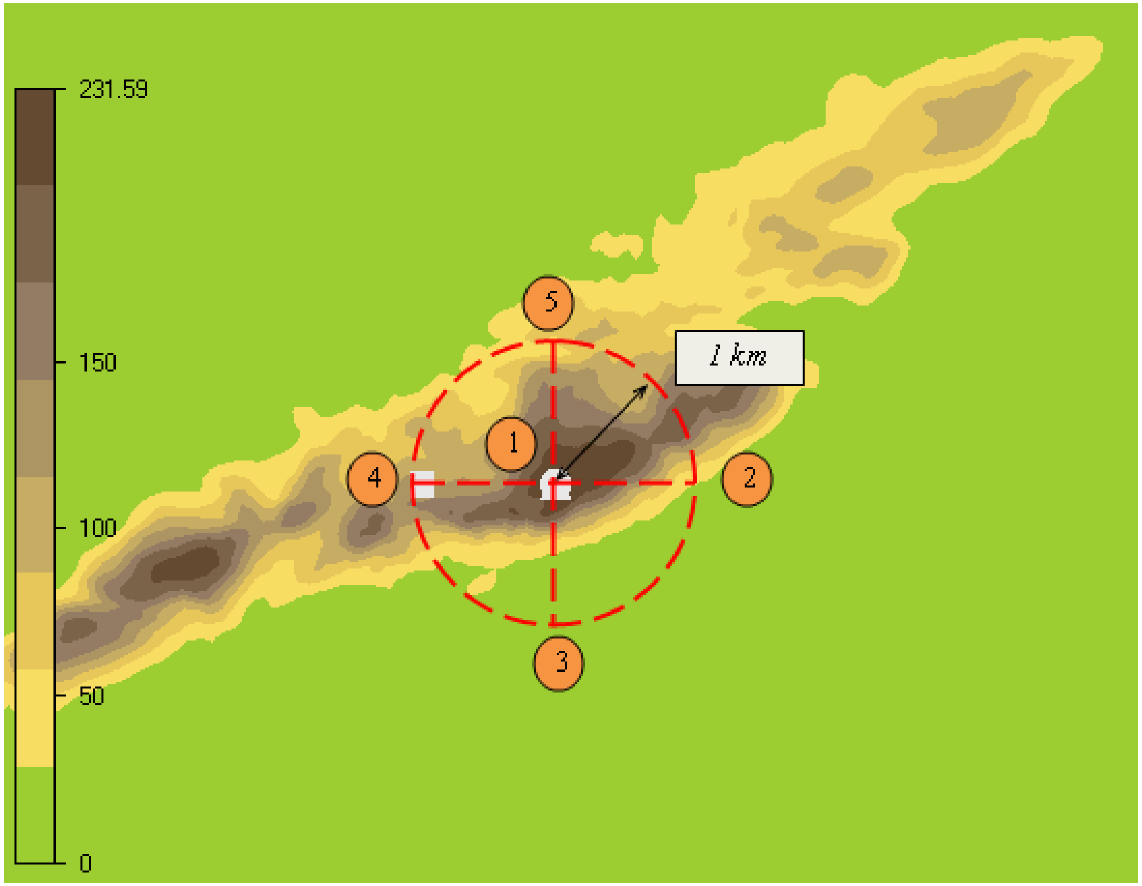


Re-distribution errors

The re-distribution imposes a smoothing of the frequency distribution.

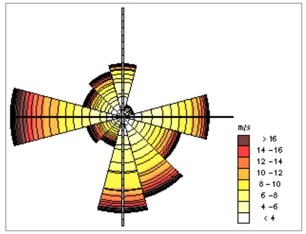
Consequently, a transferred climatology which is moved back to its original position will not be reproduced.

Hundhammerfjellet – climatology transfer



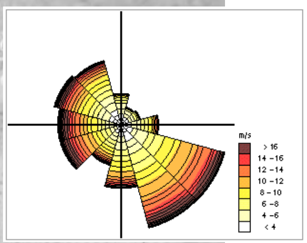
The climatology Hundhammeren is moved 1000 meters in the cardinal direction and then back to its original position.

Hundhammerfjellet – climatology transfer

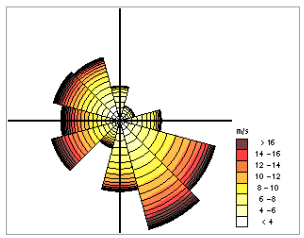


ΔAEP/AEP$_{ref}$: -10.72

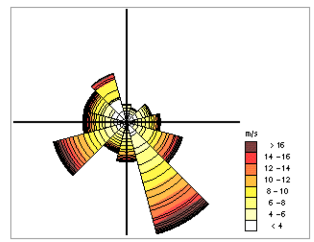
Errors in the order of 5% due to discrete representation of the climatologies. (5% + 5% = 10% when moving back and forth)



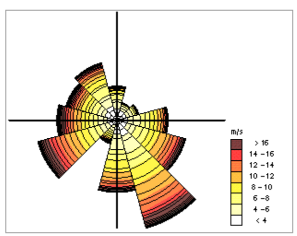
ΔAEP/AEP$_{ref}$: -0.67



AEP$_{ref}$: 6.332 (GWh/y)



ΔAEP/AEP$_{ref}$: -11.52



ΔAEP/AEP$_{ref}$: -4.08

Use the time histories instead of the frequency distribution when post-processing the wind field simulations.

Weighting of climatology data

Summary:

The representation of climatology data by a frequency distribution introduces significant interpolation errors.

Finer resolution, more sectors and bins would reduce the errors, the best would be to use time series.

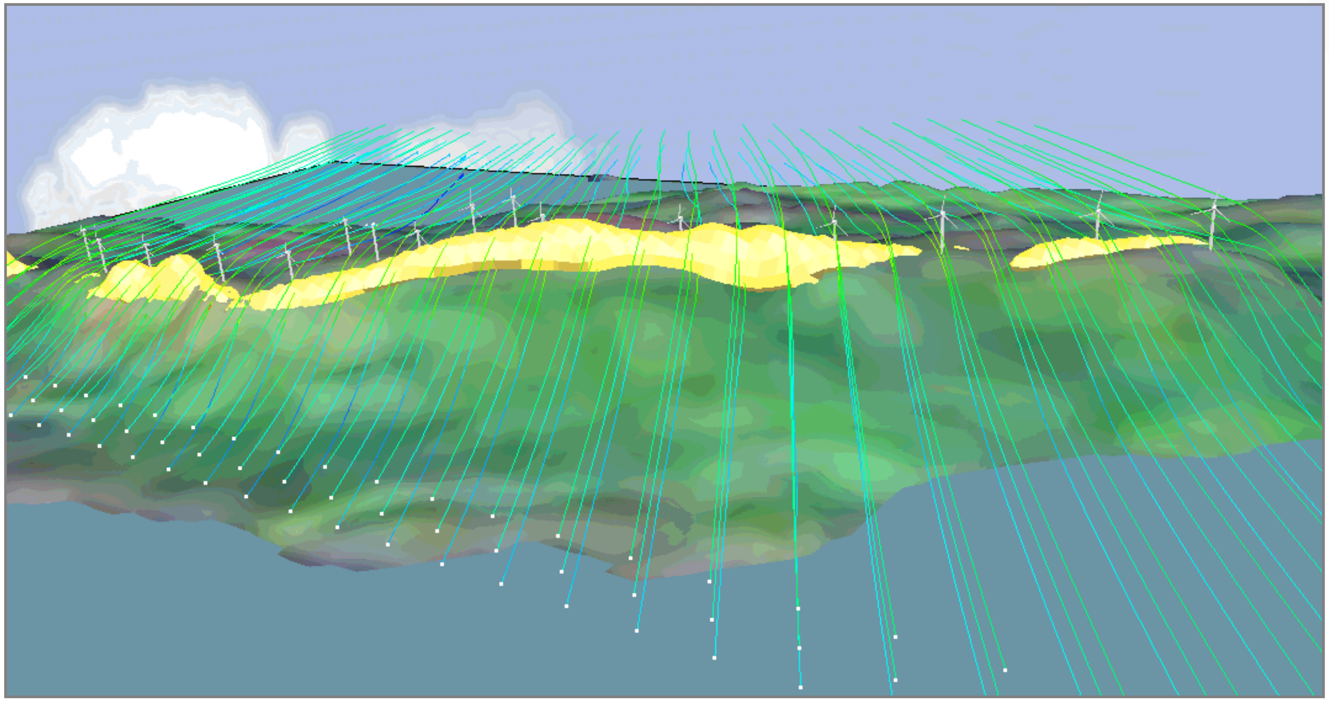
Next:

Power curve correction

windsim
When the terrain gets rough

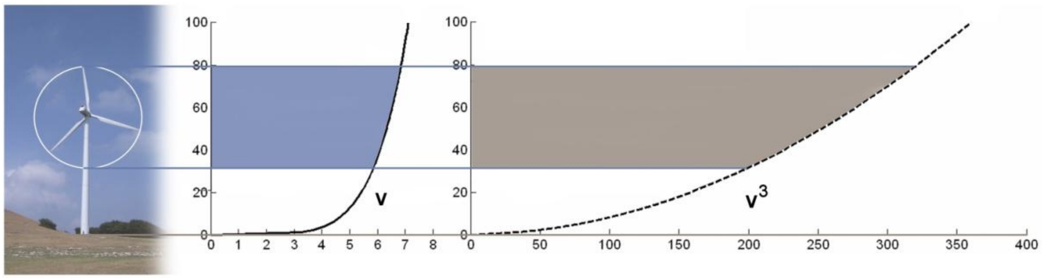
Hundhammerfjellet – negative shear

Speed-ups are observed over hills with maximum wind speed near the ground followed by a region with a negative shear

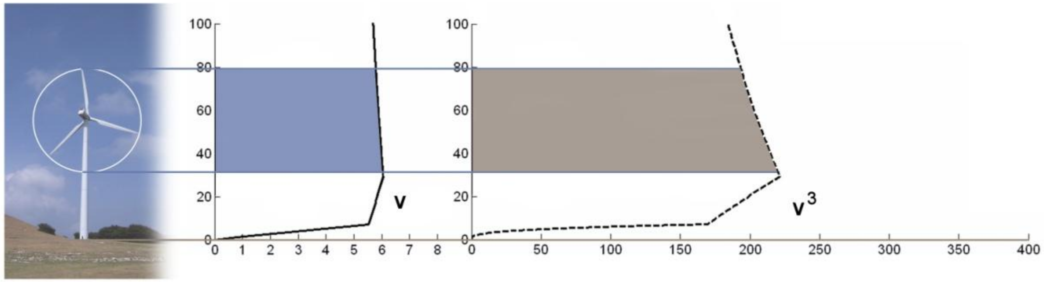


Wind field from sector 6 (150 degrees), isosurface showing the highest wind speeds below hub height

Energy content – wind profiles



Energy content for logarithmic wind profile



Energy content for wind profile with negative shear

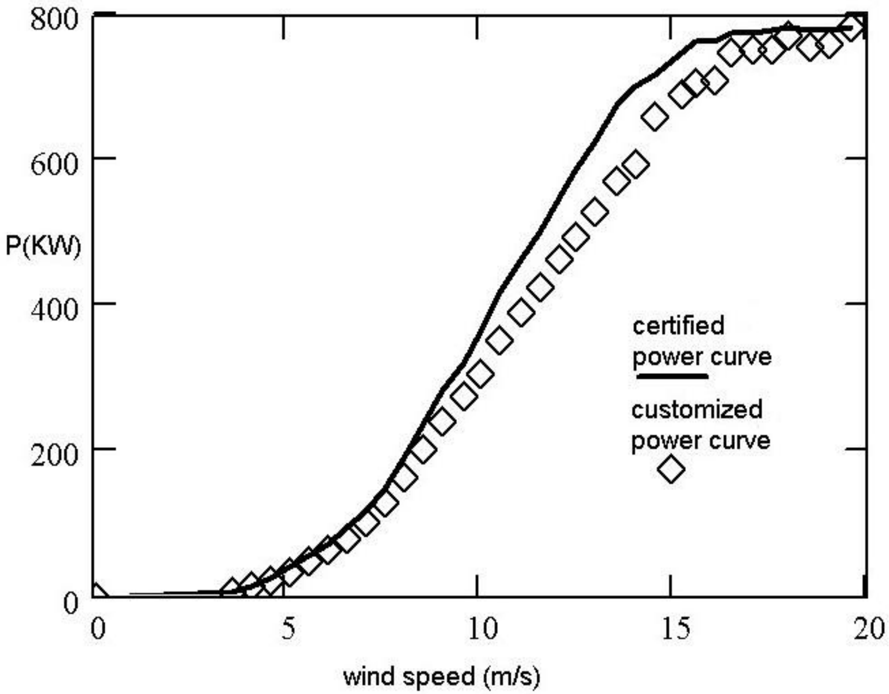
Power curve certification

Certified power curve is established at test site in plane terrain

At complex sites the certified power curve is not valid

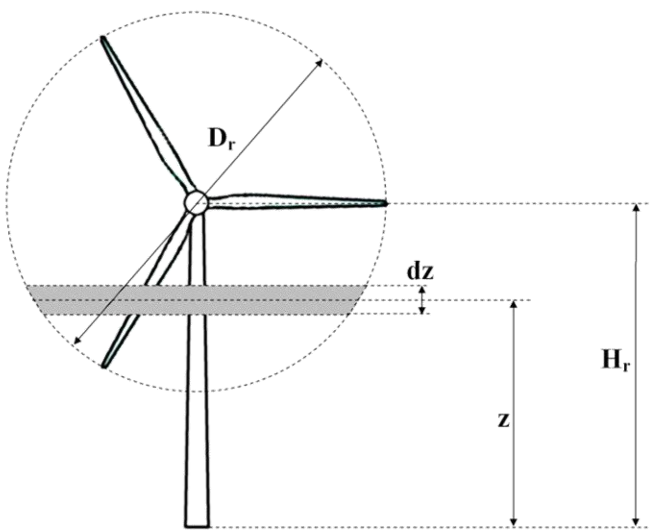
Test site

Ridge



Power curve correction procedure

$$P\left(v(z)\right) = \frac{1}{2} \cdot \frac{16}{27} \cdot \rho \cdot \int_{H_r - \left(\frac{D_r}{2}\right)}^{H_r + \left(\frac{D_r}{2}\right)} 2 \cdot \sqrt{\left(\frac{D_r}{2}\right)^2 - \left(H_r - z\right)^2} \cdot v(z)^3 \, dz$$



$$R = \frac{\text{P(numerical profile)}}{\text{P(exponential profile)}}$$

$$P_{cor}\left(v, m\right) = R\left(v, m\right) * P_{cer}\left(v\right)$$

Paper: F.Castellani F. and Franceschini G. *A new technique to improve expected aep estimation in very complex terrain*, AIAA 2005

windsim
When the terrain gets rough

Power curve correction

A ridge situation with a negative shear profile could be significantly improved with the correction procedure.

	No correction	Correction
100(Experimental/CFD)	77	96

AEP (GWh/y) for a turbine on a ridge with and without power curve correction

Conclusion

Calculation of the AEP involves many disciplines, describing complex physical phenomenon. Consequently, a simple calculation procedure can not be set up.

Basic cases show that CFD is clearly more accurate than linear methods.

Important issues

- Grid resolution
- Roughness description
- Climatology description; frequency distribution vs. time-series
- Power curve correction

More information

Booth Number 747

www.windsim.com:

- Paper and presentations
- Free WindSim evaluation copy
- Training courses: 18-20 June 2007
- User meeting: 21-22 June 2007